ELECTROMAGNETICS

07 March 2012

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Integrity ★ Service ★ Excellence

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NAME: Dr. Arje Nachman

BRIEF DESCRIPTION OF PORTFOLIO:

Interrogation (Modeling/Simulation) of Linear/Nonlinear Maxwell's Equations

LIST SUB-AREAS IN PORTFOLIO:

Theoretical Nonlinear Optics

Wave Propagation Through Complex Media

Fundamentals of Antenna Design/Operation

Fundamentals of Effects of EM Exposure on Circuitry

Scientific Challenges

- **Wave Propagation Through Complex Media**

Details of time-domain dynamics of EM pulses through Dispersive, Conductive, and/or Random/Turbulent media

Research provides optimism that the class of waveforms termed <u>Precursors</u> have the potential to upgrade imaging quality.

- **Antenna Design/Operation**

Suitable *PARTNERSHIPS* of MATERIALS and GEOMETRY can deliver man-made composites which exhibit novel EM attributes. Such METAMATERIALS include: NIMs, PBGs, and "Unidirectional" composites.

Growing reliance on small UAVs drives the need to miniaturize antennas and make them more responsive.

Scientific Challenges

- ## Nonlinear Optics

Fundamental modeling/simulation research which addresses concerns with femtosecond filament arrangements and plasma channel characteristics.

Advances in modeling/simulation of fiber and solid state lasers to guide the development of compact, high energy systems.

- ## RF Effects on Circuitry

Identification of waveforms which produce various realizations of circuit upset (includes chaos).

Complicated by the fact that effects are likely to be dictated by the activity of the circuit (eg, routines being run by laptop).

MURIs

This portfolio has an existing MURI (Ultrashort Laser Pulses) which just completed its 1st year.

Two more MURIs supportive of the portfolio subarea "Wave Propagation Through Complex Media" will be starting:

- "Deep Optical Turbulence Physics"
- "High Power, Low-Loss, Artificial Materials for Transformational Electromagnetics"

Mathematical Modeling and Experimental Validation of Ultrafast Nonlinear Light-Matter Coupling Associated with Filamentation in Transparent Media

MURI PMs---Dr Arje Nachman and Dr Enrique Parra

J.V. Moloney	ACMS/OSC
M. Kolesik	ACMS/OSC
P. Polynkin	ACMS/OSC
S.W. Koch	OSC
N. Bloembergen	OSC
A.C. Newell	ACMS/Math
K. Glasner	ACMS/Math
S. Venkataramani	ACMS/Math
M. Brio	ACMS/Math

A. Becker
A. Jaron-Becker
H. Kapteyn
M. Murnane

C. Durfee
J. Squier

W.P. Roach AFRL/RD

D. Christodoulides

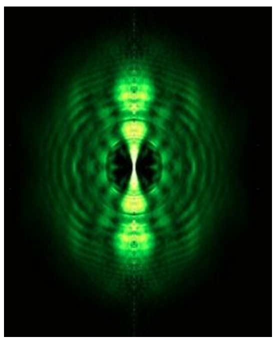
R. Levis

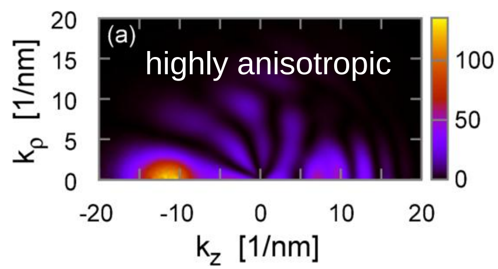
A. Gaeta

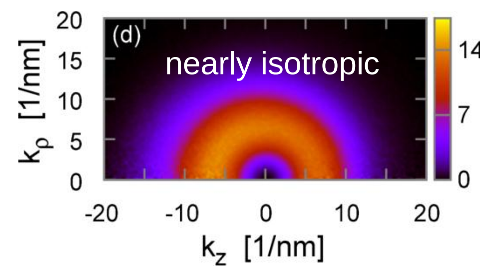
New State of Matter: Uncorrelated Electrons to Plasma Transition

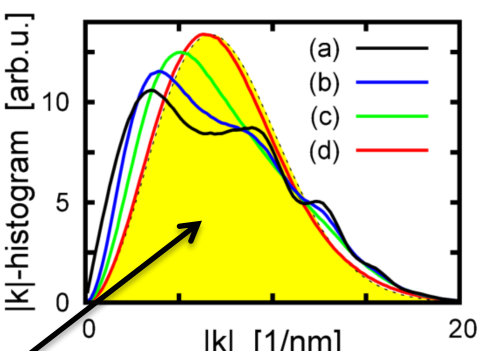
B. Pasenow, M. Brio, J.V. Moloney, S. W. Koch, S.H. Chen, A. Becker, and A. Jaron-Becker

- **MURI collaboration between University of Arizona and University of Colorado**
- **USP ionization: highly anisotropic uncorrelated electron distributions**
- **Relaxation/isotropization of non-equilibrium distributions due to Coulomb scattering**
- **THz EM response: evolution of loss of anisotropy and carrier density (plasmon pole)**

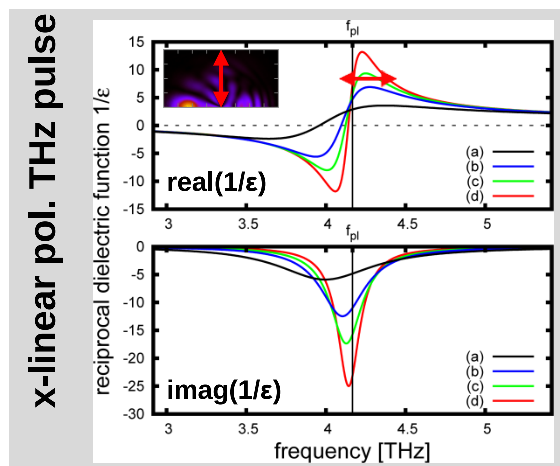


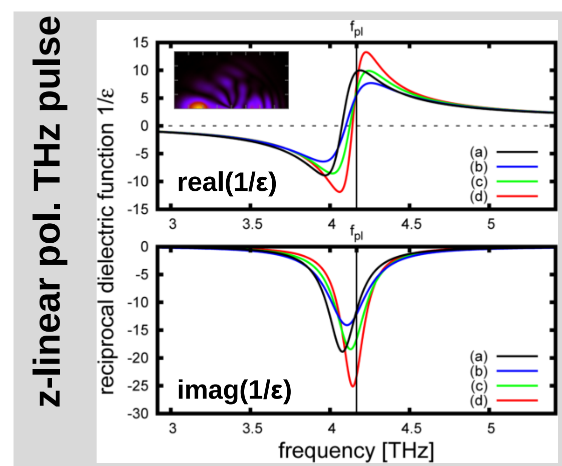






Fermi-Dirac electron momentum distribution in isotropic plasma



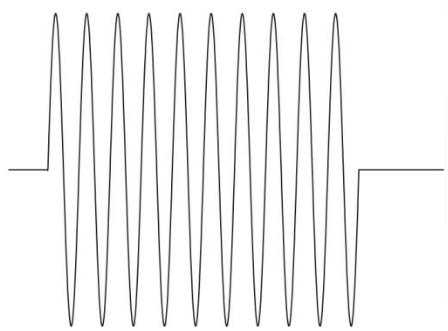


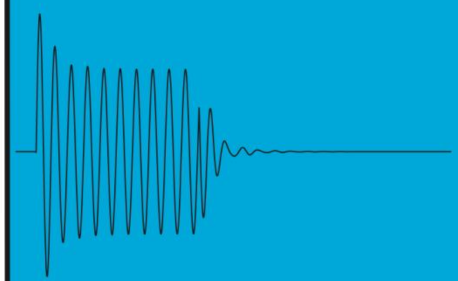
FORMATION of PRECURSORS and their *ALGEBRAIC DECAY* with DISTANCE into DISPERSIVE MEDIA

Dr Kurt Oughstun/UVt and Dr Natalie Cartwright (YIP)/SUNY-NewPaltz

AIR

MATERIAL
water, etc





Electric field component before incidence:
SQUARE-WAVE MODULATED SINE

Electric field component of the transmitted pulse.

Electric field component of the propagated pulse. This precursor decays as the inverse square root of z and contains a generous bandwidth.

Note: The CW version of the above sinusoid would experience exponential decay!

Z = 0

Z > 0

THE PROPAGATED PULSE

how they did it

The electric field component of the propagated pulse on any plane z > 0 is given by

$$E(z,t) = \frac{1}{2\pi}\mathrm{Re}\left\{ i\int_{ia-\infty}^{ia+\infty} T_E(\omega)\tilde{E}(z<0,\omega)e^{i\tilde{k}(\omega)z - i\omega t}\,d\omega \right\},$$

where $\tilde{k}(\omega) = \frac{\omega}{c}n_2(\omega)$ **is the complex wave number of the dielectric material.**

$$T_E(\omega) = \frac{2}{1+n_2(\omega)} \qquad n_2(\omega) = \sqrt{1 - \frac{\omega_p^2}{\omega^2 - \omega_0^2 + 2i\delta\omega}}$$

For values of ct/z= $\theta \leq 1$ **the contour may be closed in the upper half plane and application of Jordan's lemma gives** $E(z,t) = 0, \quad t < z/c.$

This integral representation of the field has no known exact solution when ct/z>1

Asymptotic methods, such as saddle point methods, may be used to find an approximation to the propagated pulse.
These methods require the deformation of the Bromwich contour through the valleys of the accessible saddle points of the complex phase function

$$\phi(\omega,\theta) = i\omega[n(\omega) - \theta], \quad \theta = \frac{ct}{z}$$

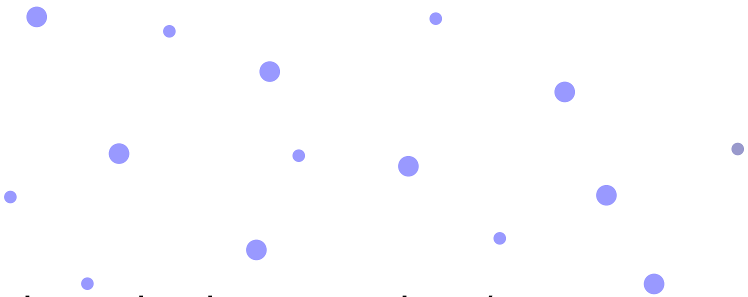
which is completely characterized by the dielectric material.

ACTIVE INFRARED IMAGING THROUGH SPARSE DISCRETE MEDIA

Drs. Elizabeth and Marek Bleszynski
Monopole, Inc

PROJECT OBJECTIVE

investigate possibility of using wide-band, infrared (IR) pulses in imaging through media composed of sparsely distributed discrete particles, such as clouds, fog, dust, or smoke



"sparse" medium: mean-free path* much larger than average separation between scatterers
*mean free path is the penetration depth over which intensity decreases by 1/e so sparse=mean free path corresponding to the highest frequencies in the pulse spectrum is much larger than average separation between scatterers.

PROPAGATION OF A WIDE-BAND IR PULSE THROUGH SPARSE DISCRETE MEDIA

example: **a trapezoidally modulated IR pulse propagating through a cloud**

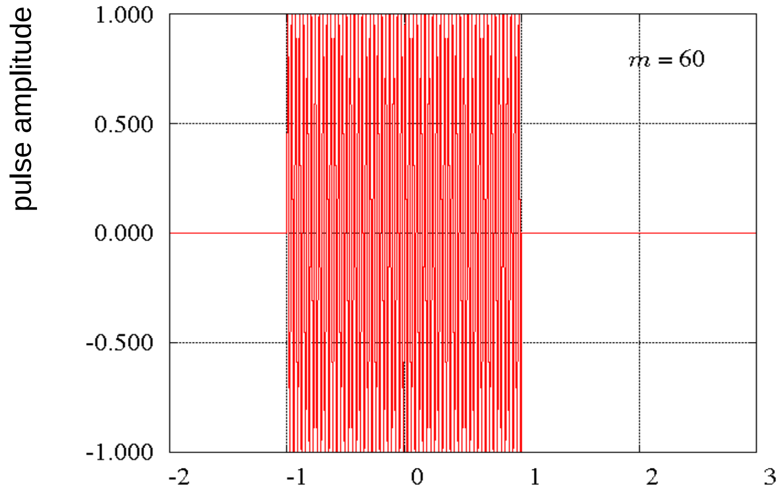
pulse parameters:

- **carrier wavelength: λ = 10μm (ν = 30 THz)**
- **number of cycles in the pulse: *m* = 60**
- **rise/fall time: 0.05 of the carrier period**

cloud parameters:

- **average droplet radius: *a* ~ 5μm**
- **average droplet-droplet distance: *R* ~ 1 mm**

transmitted pulse

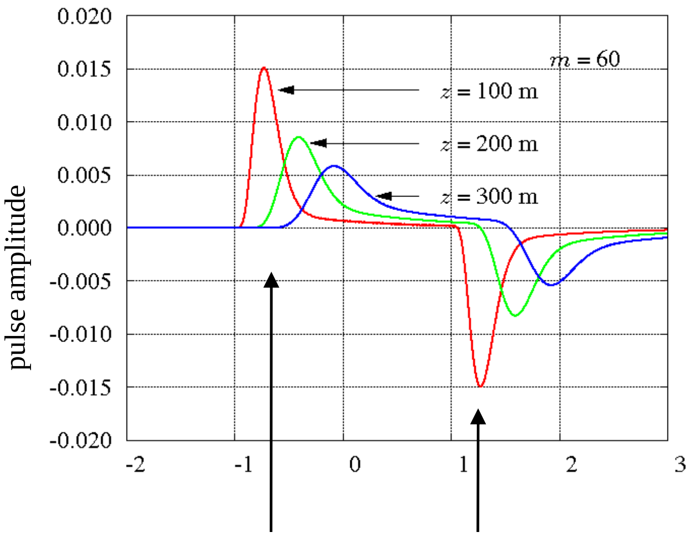


time in picoseconds

PROPAGATION OF A WIDE-BAND IR PULSE THROUGH SPARSE DISCRETE MEDIA

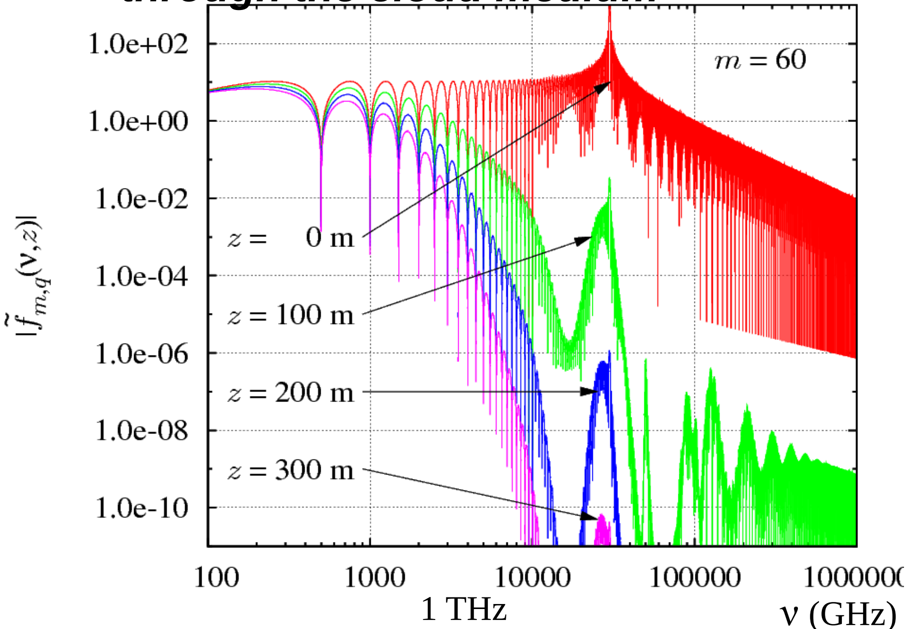
- *medium as a filter attenuating high frequencies*
- *evolution of the propagating pulse into a Brillouin precursor*

pulse amplitude after propagating z = 100m, 200m, 300m through the cloud medium



Brillouin precursor-type structures associated with the leading and trailing edges of the transmitted pulse

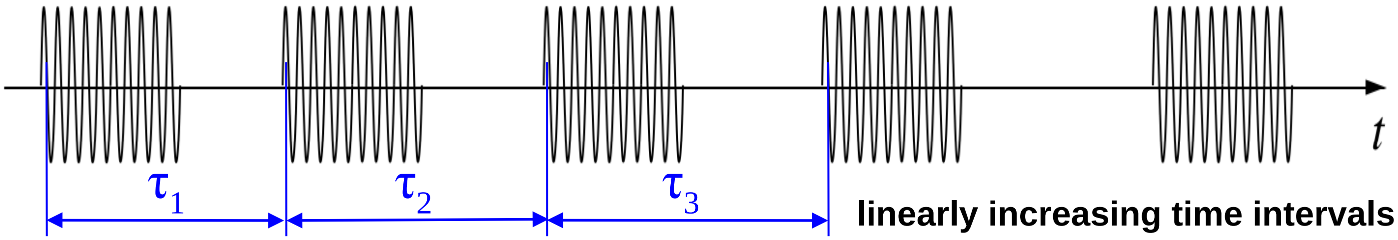
pulse spectrum after propagating z = 100m, 200m, 300m through the cloud medium



- *the transmitted pulse spectrum has a significant amount of low-frequency components*
- *the high-frequency part of the spectrum is attenuated very strongly as the pulse propagates*
- *the low-frequency part of the spectrum is weakly attenuated*

PROPAGATION OF A "CHIRPED TRAIN OF PULSES"

generate a coherent train of N pulses (with small rise/fall times) emitted at linearly increasing pulse-pulse intervals



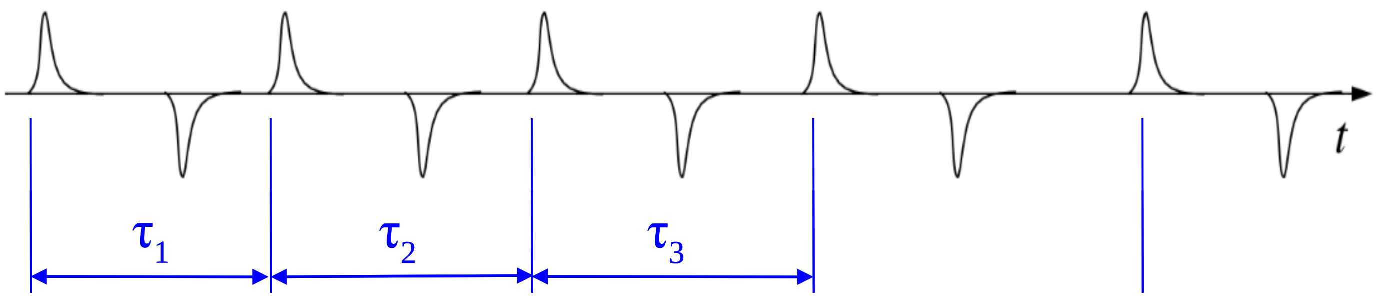
linearly increasing time intervals τ_p between pulses

chirped train characterized by: effective center frequency and effective bandwidth

$$\nu_C = \frac{1}{\langle \tau \rangle}$$

$$B_C = \frac{1}{\tau_{min}} - \frac{1}{\tau_{max}}$$

after passing through clouds the pulse train becomes a train of precursor-type pulses associated with leading and trailing edges of the transmitted trapezoidal pulses and attenuated approximately algebraically (not exponentially)



PRECURSOR SUMMARY

- **For MW (radar) imaging, it is difficult to produce square-wave modulated sinusoids.**

  But it is possible for modern radars to produce PRECURSORS!

  1. These interesting waveforms contain greater bandwidth than conventional narrow-band radar pulses,

  2. Decay algebraically with depth,

  3. Experience reduced "flash" at any media interface,

  4. Allow for easier Matched Filtering.

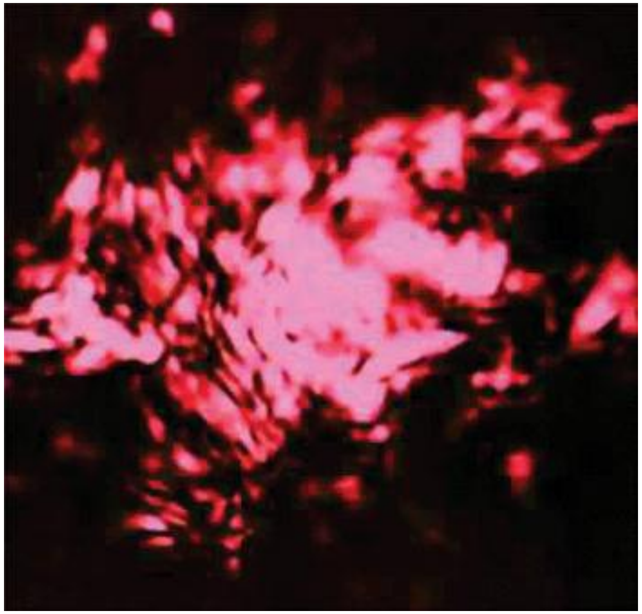
- **None of this is seriously modified by oblique incidences.**
- **For laser imaging through clouds (ladar) it is very easy to produce (nearly) square-wave modulated sinusoids, but not precursors. The cloud produces the precursor, which decays algebraically with depth. In order to compensate for the loss of the high IR frequencies (and thus detailed spatial resolution) the notion of chirping the pulse train was invented.**

Laser Beams & Turbulence

Dr Greg Gbur/ElectricalEngineering
University of North Carolina, Charlotte

Optical beam propagation in the atmosphere is hindered by atmospheric turbulence: random fluctuations of the refractive index.

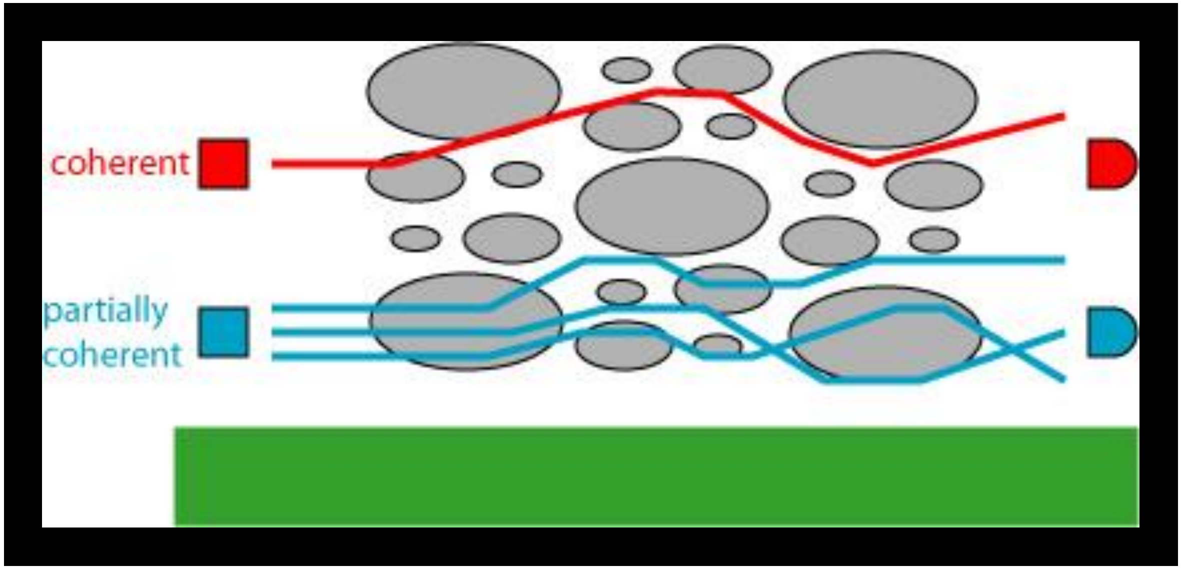
Applications such as free-space optical communications and LIDAR are adversely affected by atmospheric turbulence, which induces intensity fluctuations (scintillations).



Laser beam distorted by turbulence

'Heat shimmer' (mirage) on a hot day

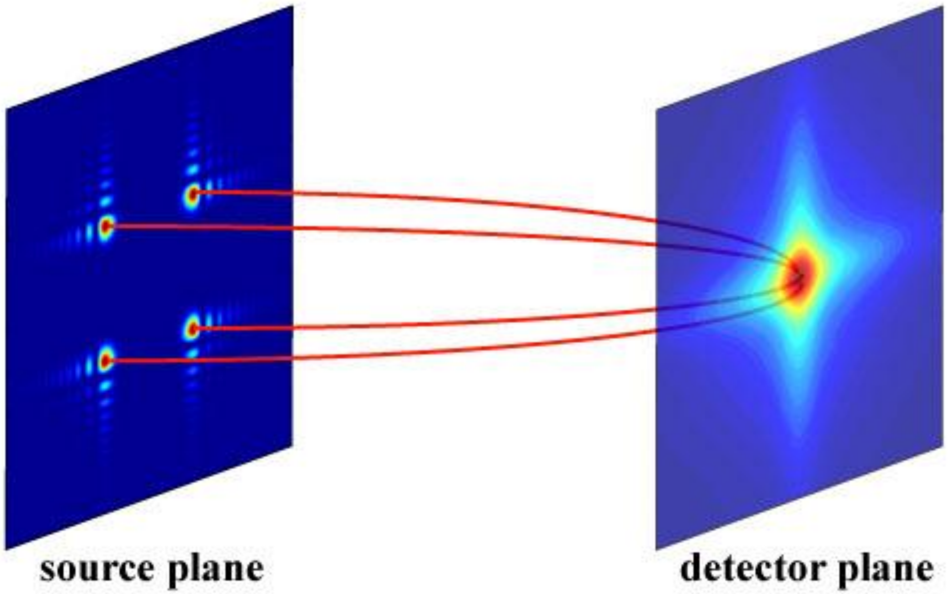
Partially Coherent Beams in Turbulence



- **A coherent laser essentially propagates its energy through a single coherent beam, which may partly or wholly miss detector**
- **The partially coherent beam sends its energy through multiple beamlets, increasing the likelihood of hitting a detector and smoothing out fluctuations**
- **Beamlets need to be significantly different, or diverse**

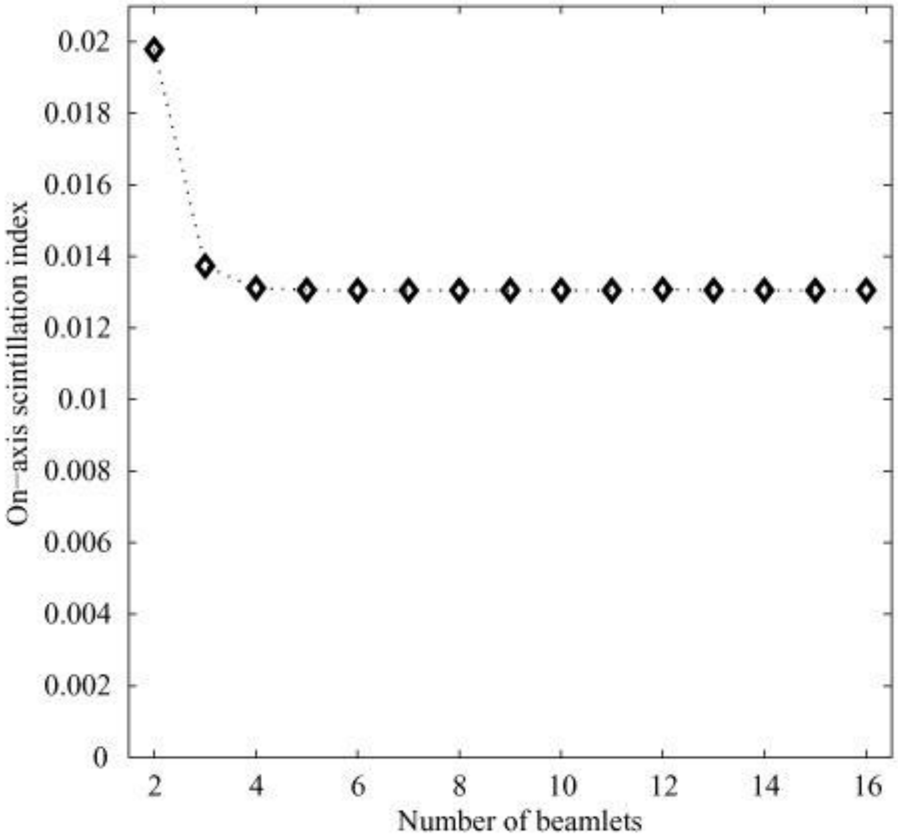
Airy Beams in Turbulence

A spatial filtering system, with an appropriate phase mask, can produce an Airy beam



Try four beamlets designed to curve together at target: each beamlet sees different turbulence but average peak intensity is at center of detector

Scintillation vs. # of Beamlets



Scintillation reaches its minimum possible value with only four beamlets!

Evidently four beamlets is "good enough" for reducing intensity variance!

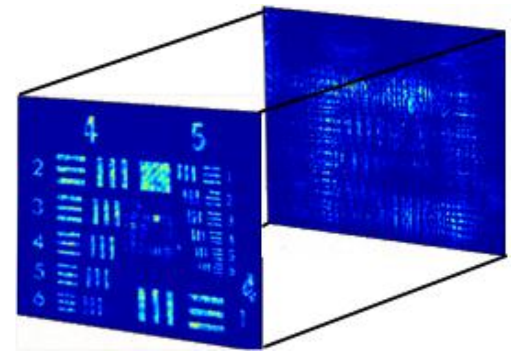
Additional beamlets are not diverse enough to provide additional improvement

Nonuniformly *polarized* beams another idea

Imaging with Spatial Nonlinearity

Dr Jason Fleischer
Electrical Engineering, Princeton

- Scalar field ψ obeys nonlinear Schrödinger equation.
- Numerical solution via split-step Fourier method.

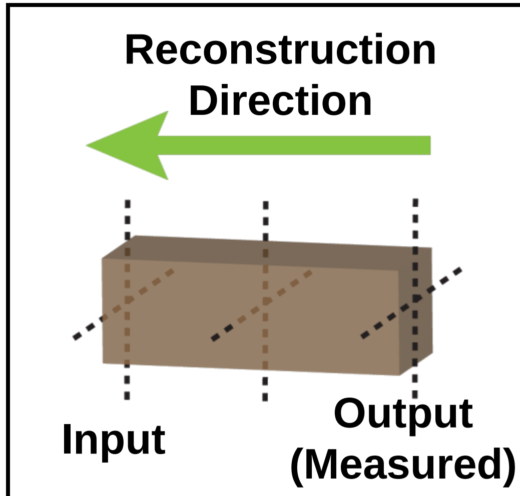


$$\frac{\partial \psi}{\partial z} = \left[\underbrace{i \frac{1}{2k} \nabla_\perp^2}_{\text{Linear}} + \underbrace{i \Delta n(|\psi|^2)}_{\text{Nonlinear}} \right] \psi \equiv \left[\hat{D} + \hat{N}(|\psi|^2) \right] \psi$$

$$\psi(x, y, z + dz) = e^{\hat{D}dz + \hat{N}dz} \psi(x, y, z)$$

$$\approx e^{\hat{D}dz} e^{\hat{N}dz} \psi(x, y, z)$$

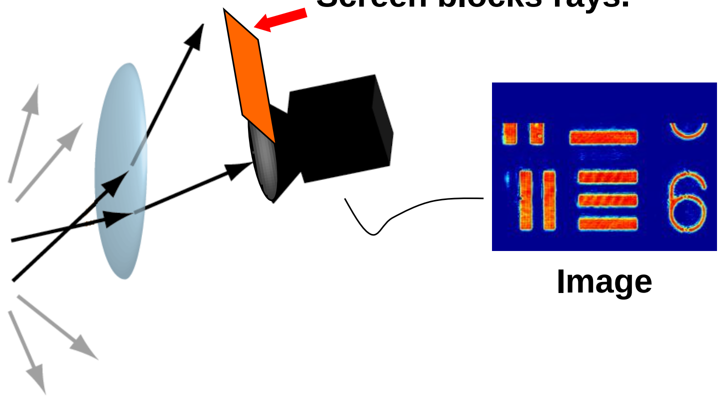
Initial value problem



Back-propagation gives *ψ(z)* if we know *ψ(z + dz)*:

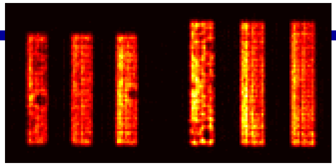
$$\psi(x, y, z) \approx e^{-\hat{N}dz} e^{-\hat{D}dz} \psi(x, y, z + dz)$$

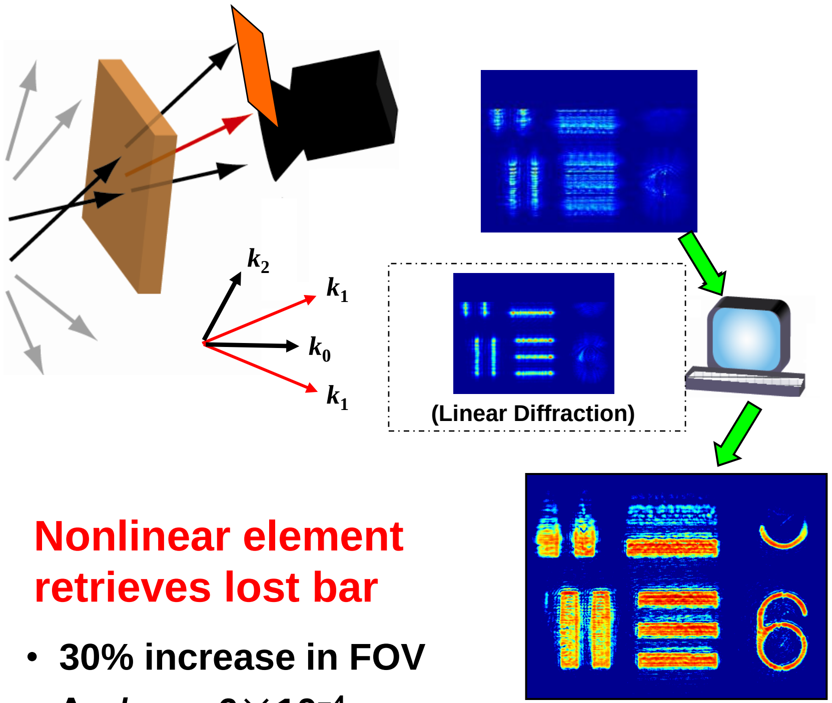
Improved imaging with NL:
field of view and resolution



$Sr_{0.75}Ba_{0.25}Nb_2O_6$

Photorefractive crystal

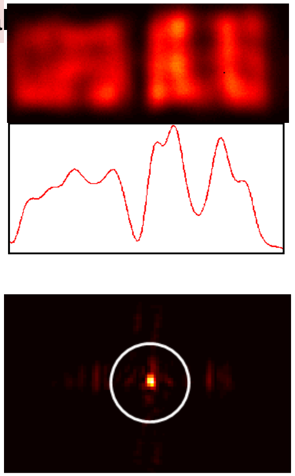




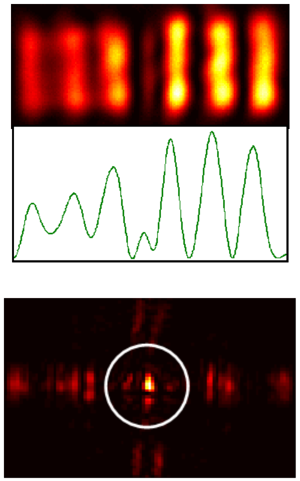
Nonlinear element retrieves lost bar

- **30% increase in FOV**
- **$\Delta n / n_0 \sim 6 \times 10^{-4}$**

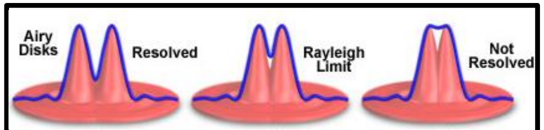
Linear Output



Nonlinear Output



$V_{linear} = 0.095$ $V_{NL} = 0.32$



Rayleigh Criterion

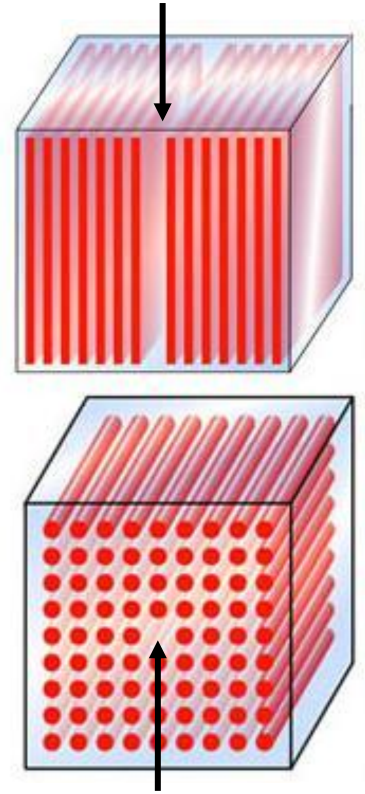
$\text{Visibility}_{\text{Rayleigh}} = 0.15$

Nonlinear Beam Deflection in Photonic Lattices with Defects

Optically-induced photonic lattice with defects: lattice spacing ~ 10 microns

defect

1D lattice



2D lattice

defect

A defect is a local abnormality inside a periodic lattice. Experimentally created 1D and 2D lattices with single-site defects are shown in the left figures.

Experimental procedure to optically "write" lattices with defects:

(1) let a laser beam pass through an amplitude mask

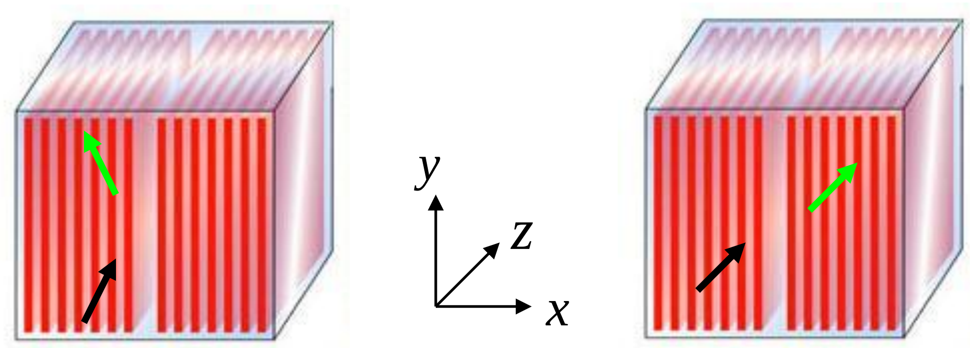
(2) use frequency filtering to remove half of the spatial frequencies

(3) slightly tilt the resulting beam

Dr Jianke Yang (Math, Univ Vermont)

Nonlinear Beam Propagation Inside Lattices with Defects, cont'd

When a nonlinear beam is launched into a lattice with a defect one finds, both theoretically and experimentally, that at small incident angles the beam is reflected by the defect but at large incident angles, the beam passes the defect.



small angle:
reflection

large angle:
transmission

z: **propagation direction**
black arrow: probe-beam direction before reaching defect
green arrow: probe-beam direction after hitting the defect

Result shows a way to use a beam's incident angle to control its propagation direction in a lattice network.

Theoretical Modeling

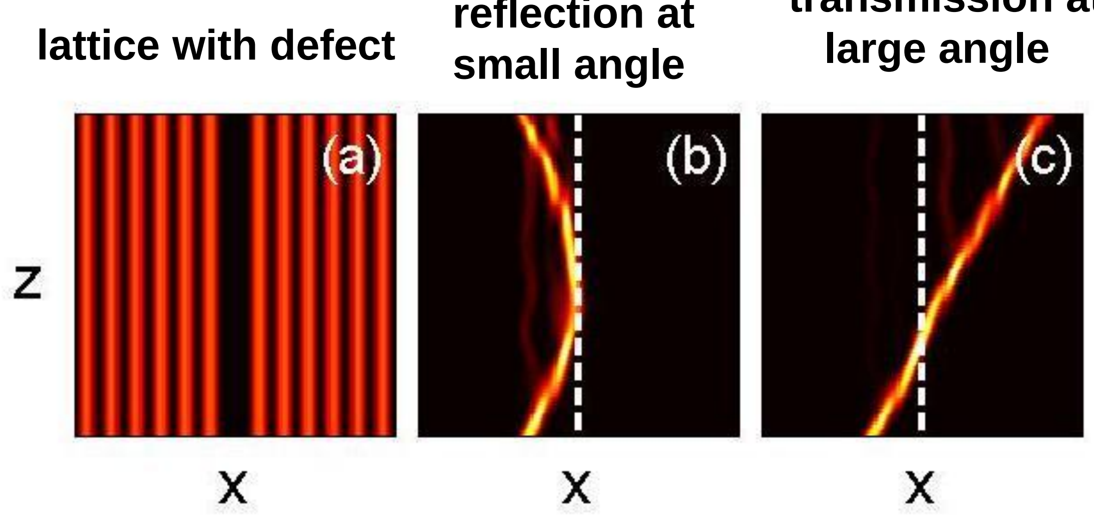
$$i\frac{\partial U}{\partial z}+\frac{1}{2k_1}\left(\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}\right)-\frac{1}{2}k_0 n_e^3 r_{33}\frac{E_0}{1+I(x,y)+|U|^2}U=0,$$

$$I=I_0\cos^2\frac{\pi x}{d}\left(1-e^{-x^2/d^2}\right),\qquad 1D\text{ case}\qquad I=I_0\cos^2\frac{\pi x}{d}\cos^2\frac{\pi y}{d}\left(1-e^{-(x^2+y^2)/d^2}\right),\qquad 2D\text{ case}$$

U: electric field; E_0 : applied dc field; r_{33}: electro-optic coefficient;

I_0 : lattice intensity; d: spacing; k_0, k_1 : wave numbers; n_e : refractive index

Simulation result:



Can a non-Hermitian operator exhibit real spectra?

VOLUME 80, NUMBER 24 PHYSICAL REVIEW LETTERS 15 JUNE 1998

Real Spectra in Non-Hermitian Hamiltonians Having $\mathcal{PT}$ Symmetry

Carl M. Bender[1] and Stefan Boettcher[2,3]
[1]Department of Physics, Washington University, St. Louis, Missouri 63130
[2]Center for Nonlinear Studies, Los Alamos National Laboratory, Los Alamos, New Mexico 87545
[3]CTSPS, Clark Atlanta University, Atlanta, Georgia 30314
(Received 1 December 1997; revised manuscript received 9 April 1998)

The answer is yes as long as the Hamiltonian respects $\mathcal{PT}$-symmetry!

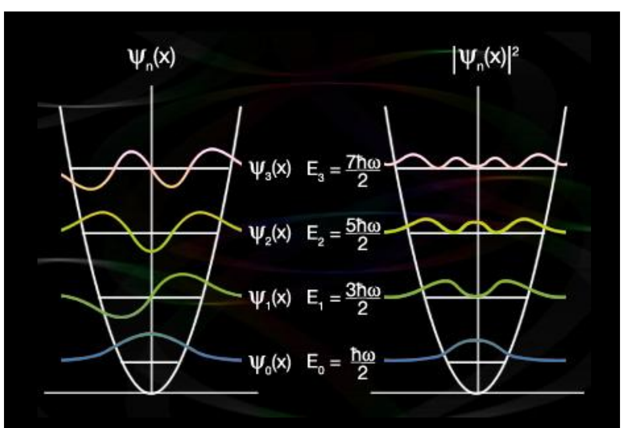
$$\hat{P}: \quad x \rightarrow -x \quad ; \quad \hat{T}: \quad t \rightarrow -t$$

$$i\hbar \frac{\partial \Psi}{\partial t} + \frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} - V(x)\Psi = 0$$

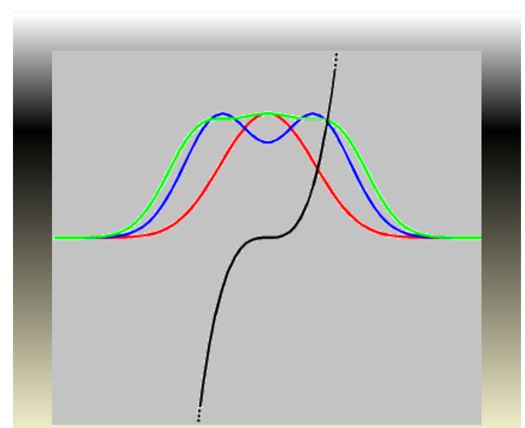
PT symmetry $\longrightarrow$ $\boxed{V(x) = V^*(-x)}$

Quantum mechanical oscillator

$V = x^2$



PT pseudo-Hermitian oscillator



$V = ix^3$

$\mathcal{PT}$ symmetry in Quantum Mechanics and Optics

Schrodinger Equation

$$i\hbar\frac{\partial\Psi}{\partial t}+\frac{\hbar^2}{2m}\frac{\partial^2\Psi}{\partial x^2}-V(x)\Psi=0$$

Time t

Planck's constant $\hbar$

Probability amplitude $\Psi(x,t)$

Complex Potential $V(x)=V_R(x)+iV_I(x)$

Paraxial Equation

$$i\lambdabar\frac{\partial E}{\partial z}+\frac{\lambdabar^2}{2}\frac{\partial^2 E}{\partial x^2}+n(x)E=0$$

Propagation distance z

wavelength $\lambdabar=\frac{1}{k}$

Electric field envelope $E(x,z)$

Complex refraction $n(x)=n_R(x)+in_I(x)$

The imaginary part $n_I(x)$ corresponds

to gain (if $n_I<0$) or loss (if $n_I>0$)

So n_R is even and n_I is odd

$\mathcal{PT}$ symmetry condition

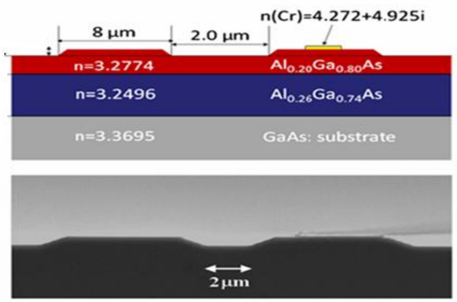
$$V(x)=V^*(-x)$$

$$n(x)=n^*(-x)$$

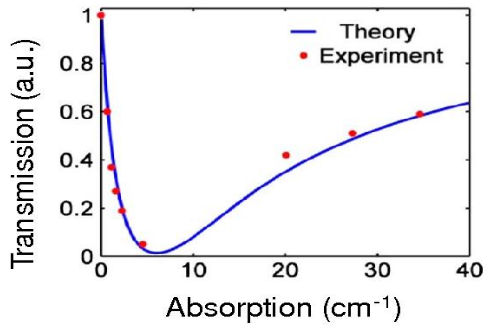
$\mathcal{PT}$ symmetric structures and devices

PT symmetry in optics can be readily established by deliberately involving gain and loss.

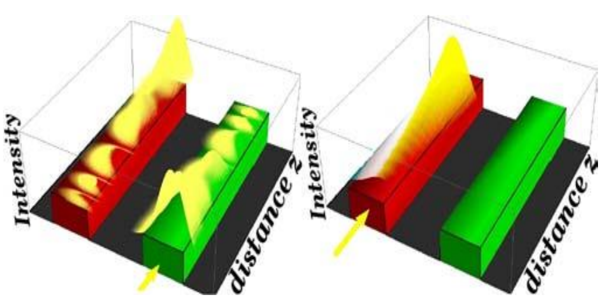
By doing so, new PT-symmetric structures and materials with useful functionalities can be envisioned.

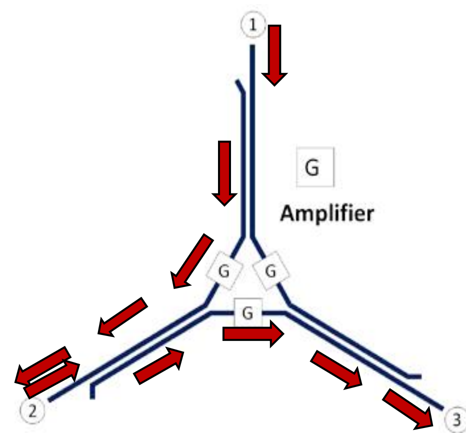


Loss-induced transparency due to PT-symmetry breaking



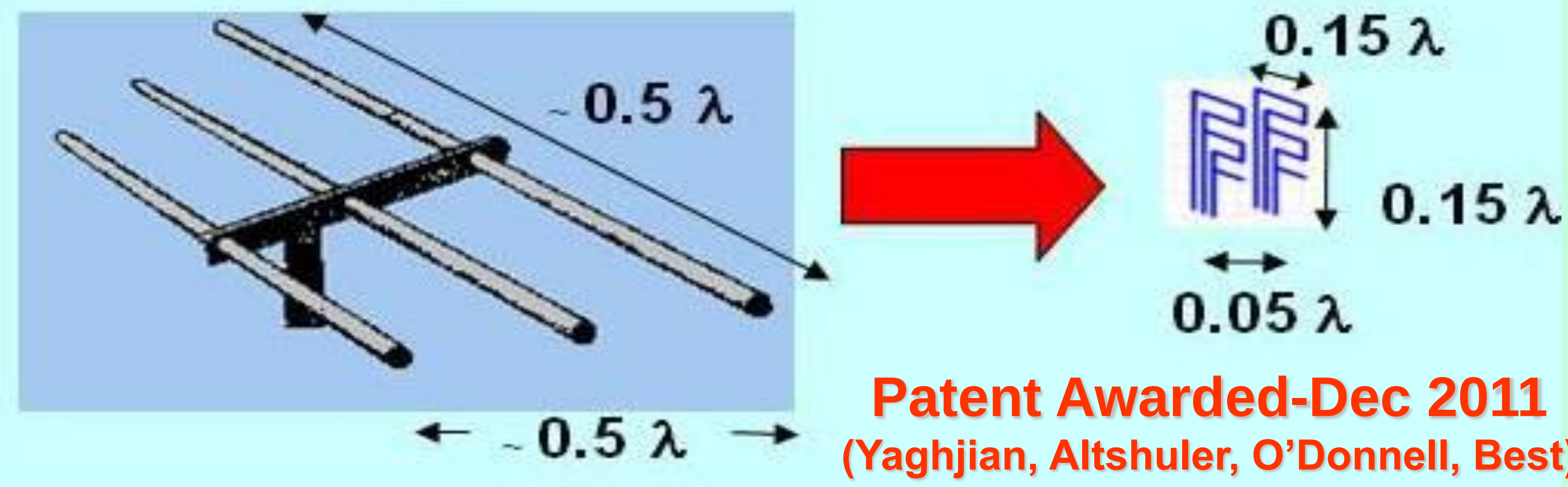
On-chip optical isolators and circulators





Dr Tsampikos Kottos (Physics/Wesleyan) and Dr Demetrios Christodoulides (Optics/UCF)

Electrically Small Supergain Arrays



Patent Awarded-Dec 2011
(Yaghjian, Altshuler, O'Donnell, Best)

- **Electrically Small (ES) arrays attain 7 dB realizable gain, 5 dB higher than any previous ES antenna.**
- **Can be used to replace much larger Yagi antennas.**
- **Paves the way for 3 or more element endfire arrays with higher gains & for multiband supergain arrays.**
- **Future research to increase bandwidth is desirable.**

RF Metamaterials for FOPEN Application

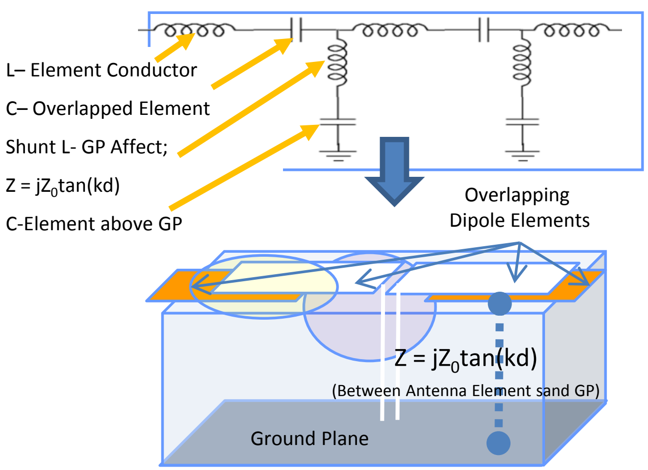
An Emulation of Anisotropy Degenerate Band Edge Tx Line Using Standard Printed Circuit

Lockheed Martin and OSU

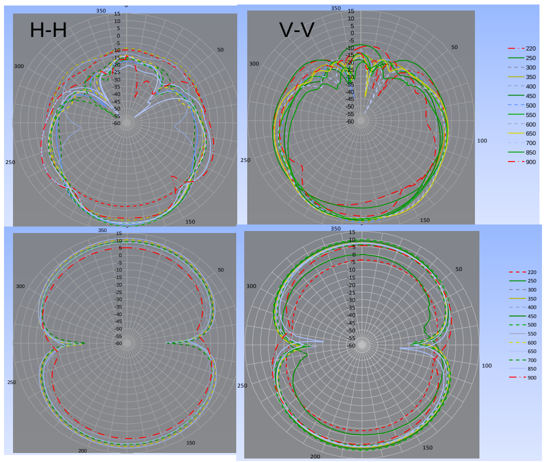
Meta FOPEN Antenna achieved the following performance (230 to 900 MHz):

- Bandwidth > 3X of State of the Art (SOA)
- Half size of SOA (24” x 24” area x 6” height)
- Light weight (5.6 Lbs)
- Dual polarized with < 20 dB cross-pol isolation
- High power capability and electronic beam steering
- Simple and low cost construction, stamdard PC and manufacturing method

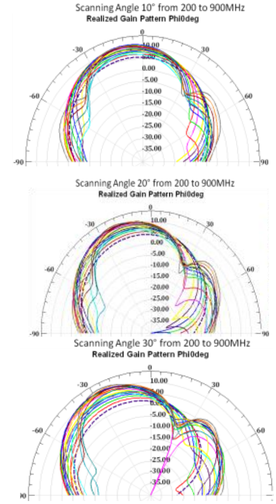
Metamaterial Equivalent Circuit Degenerate Band Edge (DBE)



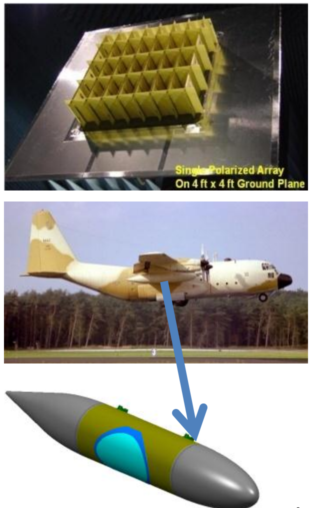
Measured Radiation Patterns



Predicted and measured Beam Steering



integration to Shadow Harvest Sensor Pod



C-130 RH Sensor Pod

ELECTROMAGNETICS LAB TASKS

Dr. Brad Kramer(AFRL/RY), "Electromagnetic Materials and Antennas" *

1. Model Electromagnetically Small Antennas: superdirective, wide-band, conformal

Dr. Ilya Vitebskiy (AFRL/RY) "Metamaterials for the Enhancement of Light-Matter Interaction" *

1. Performance enhancement of various transceivers

Dr. Saba Mudaliar (AFRL/RY), "EM Scattering Studies"

1. Predict scattering from clutter and rough surfaces

Dr. Kris Kim (AFRL/RY), "Predict Far-Field RCS via Near-Field Data"

(Dr.) Jason Parker (AFRL/RY), "Moving Target Radar Feature Extraction"

Dr. Nicholas Usechak (AFRL/RY), "Dynamics of Reconfigurable/Agile Quantum Dot Lasers" **

1. Investigate control of amplitude-phase coupling in Quantum Dot laser systems

Dr. Timothy Clarke (AFRL/RD), "Modeling of HPM Effects on Digital Electronics" **

1. Derive mathematical model predicting effects (upset) on digital electronics when exposed to various incident EM pulses

Dr. Danhong Huang (AFRL/RV), "Models for Ultrafast Carrier Scattering in Semiconductors"

1. Model IR amplifier for extremely weak signals and distant targets

Dr. Analee Miranda (AFRL/RY), "Detection and Imaging of Underground Facilities Using SAR Data" *

Dr. Matthew Grupen (AFRL/RY), "Electronic Band Structure for High Speed Quantum Electron Device Simulation"

1. Modeling/Simulation of quantum tunneling devices

Dr. Iyad Dajani (AFRL/RD), "Time Dynamics of Stimulated Brillouin Scattering in Fiber Amplifiers with Frequency Modulation"

1. SBS suppression research to realize higher power in narrow linewidth fiber amps

Dr. Erik Bochove (AFRL/RD) "Modeling of Large Nonlinear Passively Phased Fiber Laser Arrays" **

*=New for FY12 **=Renewal for FY12

Subareas Funding Trends

- Wave Propagation Through Complex* Media

  * Dispersive, Conductive, Random/Turbulent, Man-Made Composites

- Antenna Design/Operation

- Effects of EM Exposure on Circuitry
- Nonlinear Optics

  (MURI on "Propagation of Ultrashort Laser Pulses through Transparent Media" began 1 Oct 2010)

Connections with Other Organizations

- **ARO**

  Extensive interaction with Dr Richard Hammond/ARO on UltraShort Laser Pulse propagation through air

  - Dr Hammond served on my FY10 USLP MURI evaluation panel and I served on his FY11 USLP MURI panel

- **JTO**

  I manage the JTO MRI "High Power Lasers Using Optically Pumped Semiconductor Laser (OPSL) Concepts" which ends in Aug 2012

- **NRO**
  - Extensive discussions/visits regarding impact of 6.1 research on NRO needs
  - Arranged for 2 PIs to participate in the FY12 NRO Seminar series

Connections with Other Organizations

- **ONR**

  MURI (U Maryland) "Exploiting Nonlinear Dynamics for Novel Sensor Networks" managed by Dr. Michael Shlesinger, ONR

  I serve on this ONR MURI panel

  Negative Index Media MURI

  Attended review of ONR (Dr. Mark Spector) NIM Metamaterials MURI